Transient Thermohydraulic Heat Pipe Modeling: Incorporating THROHPUT into the CÆSAR Environment

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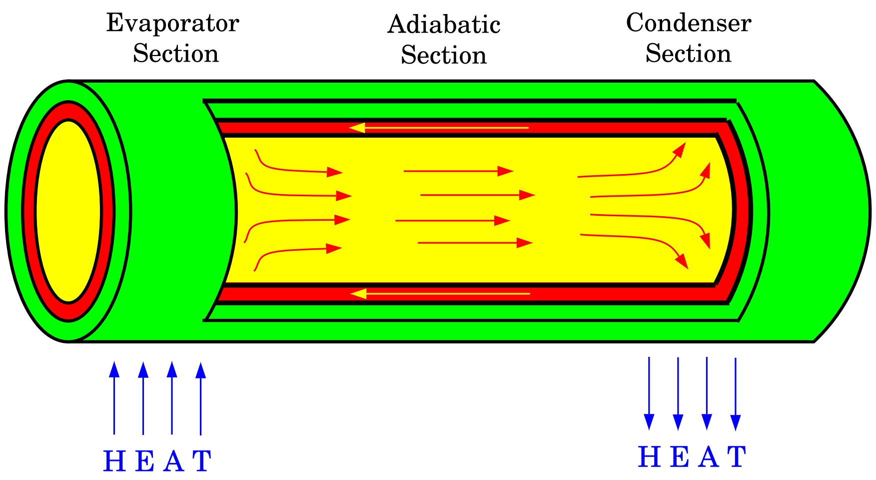
This presentation and additional information can be found on the THROHPUT home page at

`http://www.lanl.gov/THROHPUT` or `http://THROHPUT.com`

Outline

- The THROHPUT Code
  - Modeled Phenomena
  - Numerical Models
  - Main Equation Set
  - Later Modifications
- Results
- CÆSAR Computational Physics Environment
- THROHPUT Future Work

Heat Pipe Modeling – The THROHPUT Code



- THROHPUT stands for
  Thermal Hydraulic Response Of Heat Pipes Under Transients

- Developed as a Research Code for my Ph. D. Thesis

- Initial Problem:
  - Cylindrical Lithium Heat Pipe (SP-100)
  - Three Phases of Lithium & Noncondensable Gas
  - Molybdenum Wall
  - Sintered or Annular Screen Wick
  - Startup from a Frozen State to Steady State Operation
  - Space-based or Terrestrial

THROHPUT Capabilities: Modeled Phenomena

- Radial and Axial Convection
- Radial and Axial Conduction
- Mass & Heat Transfer at Wick Surface
- Surface Tension (Capillary Pressure) via separate gas and liquid pressures
- Liquid Recession into the Wick
- Pooling into the Core
- Axial Diffusion and Effusion

THROHPUT Capabilities: Numerical Models

- Main Equation Set
  - Area-Averaged Navier Stokes Equations
  - Fully-Implicit Transient Solution via a Newton Iteration
- Auxiliary Models
  - Parabolic Radial Temperature Distribution
  - Two Capillary Pressure Models
  - Radial and Axial Melt Front Propagation
  - Diffusion – Dusty Gas Model
  - All auxiliary models solved implicitly with main equation set

Main Equation Set Color Key

Time Derivative terms

Convective terms

Interphasic/Intercomponent Transfer terms

Diffusion terms

PdV-like terms

Conduction terms

$\overrightarrow{\nabla} P$ terms

Friction terms

Body Force terms

Main Equation Set: Mass Conservation

Mixture of Gases Continuity:

$$\frac{\partial}{\partial t}(\alpha_m \rho_m) + \frac{\partial}{\partial z}(\alpha_m \rho_m V_m) = \sum_{x=l,s} \Gamma_{xg}$$

Noncondensable Gas Continuity:

$$\frac{\partial}{\partial t}(\alpha_m \rho_m X_n) + \frac{\partial}{\partial z}(\alpha_m \rho_m X_n V_m) = \frac{\partial}{\partial z}\left(\alpha_m D_n^X \frac{\partial X_n}{\partial z}\right) + \frac{\partial}{\partial z}\left(\alpha_m D_n^\rho \frac{\partial \rho_m}{\partial z}\right)$$

Liquid Continuity:

$$\epsilon_v \frac{\partial}{\partial t}(\alpha_l \rho_l) + \epsilon_v \frac{\partial}{\partial z}(\alpha_l \rho_l V_l) = \sum_{x=g,s} \Gamma_{xl}$$

Solid Continuity:

$$\epsilon_v \frac{\partial}{\partial t}(\alpha_s \rho_s) = \sum_{x=g,l} \Gamma_{xs}$$

Main Equation Set: Energy Conservation

Mixture of Gases Internal Energy:

$$\frac{\partial}{\partial t}\left(\alpha_m \rho_m U_m\right) + \frac{\partial}{\partial z}\left(\alpha_m \rho_m U_m V_m\right) = -P_m\left(\frac{\partial}{\partial z}\left(\alpha_m V_m\right) + \frac{\partial \alpha_m}{\partial t}\right) + \frac{\partial}{\partial z}\left(\alpha_m k_m \frac{\partial T_m}{\partial z}\right)$$
$$+\frac{\partial}{\partial z}\left(\alpha_m D_n^X \left(h_n - h_g\right)\frac{\partial X_n}{\partial z}\right) + \frac{\partial}{\partial z}\left(\alpha_m D_n^\rho \left(h_n - h_g\right)\frac{\partial \rho_m}{\partial z}\right) + \sum_{x=l,s}\left(Q_{xm} + Q_{xg}^\Gamma\right)$$

Liquid Internal Energy:

$$\epsilon_v \frac{\partial}{\partial t}\left(\alpha_l \rho_l U_l\right) + \epsilon_v \frac{\partial}{\partial z}\left(\alpha_l \rho_l U_l V_l\right) = -\epsilon_v P_l\left(\frac{\partial \alpha_l V_l}{\partial z} + \frac{\partial \alpha_l}{\partial t}\right) + \epsilon_v \frac{\partial}{\partial z}\left(\alpha_l k_l \frac{\partial T_l}{\partial z}\right)$$
$$+ \sum_{x=m,s,w} Q_{xl} + \sum_{x=g,s} Q_{xl}^\Gamma$$

Solid Internal Energy:

$$\epsilon_v \frac{\partial}{\partial t}\left(\alpha_s \rho_s U_s\right) = \epsilon_v \frac{\partial}{\partial z}\left(\alpha_s k_s \frac{\partial T_s}{\partial z}\right) + \sum_{x=m,l,w} Q_{xs} + \sum_{x=g,l} Q_{xs}^\Gamma$$

Wall Internal Energy:

$$\rho_w c_{p_w} \frac{\partial T_w}{\partial t} = \frac{\partial}{\partial z}\left(\alpha_w k_w \frac{\partial T_w}{\partial z}\right) + Q_{in} + \sum_{x=l,s} Q_{xw}$$

Main Equation Set: Momentum Conservation

Mixture of Gases Momentum:

$$\frac{\partial}{\partial t}\left(\alpha_m \rho_m V_m\right) + \frac{\partial}{\partial z}\left(\alpha_m \rho_m V_m^2\right) = -\alpha_m \frac{\partial P_m}{\partial z} - \mathcal{F}_m V_m + \alpha_m \rho_m g_z$$

Liquid Momentum:

$$\epsilon_v \frac{\partial}{\partial t}\left(\alpha_l \rho_l V_l\right) + \epsilon_v \frac{\partial}{\partial z}\left(\alpha_l \rho_l V_l^2\right) = -\epsilon_v \alpha_l \frac{\partial P_l}{\partial z} - \mathcal{F}_l V_l + \epsilon_v \alpha_l \rho_l g_z$$

Main Equation Set: Constitutive Equations

Mixture State:	$P_m = \rho_m T_m \left(X_n R_n + \left(1 - X_n\right) R_g\right)$
Liquid State:	$\rho_l = \rho_l \left(P_l, T_l\right)$
Solid State:	$\rho_s = \rho_s \left(T_s\right)$
Volume Fraction Sum:	$\sum_{x=m,l,s} \quad \alpha_x = 1$
Capillary Pressure Relation:	$P_m - P_l = \mathcal{L}\left(\Delta P_{cap}\left(\alpha_m\right)\right)$

Grand total of 15 equations, 15 unknowns at each node.

System variables are:
ρ_m, ρ_l, ρ_s, X_n, α_m,α_l, α_s, P_m, P_l, V_m, V_l, T_m, T_l, T_s and T_w.

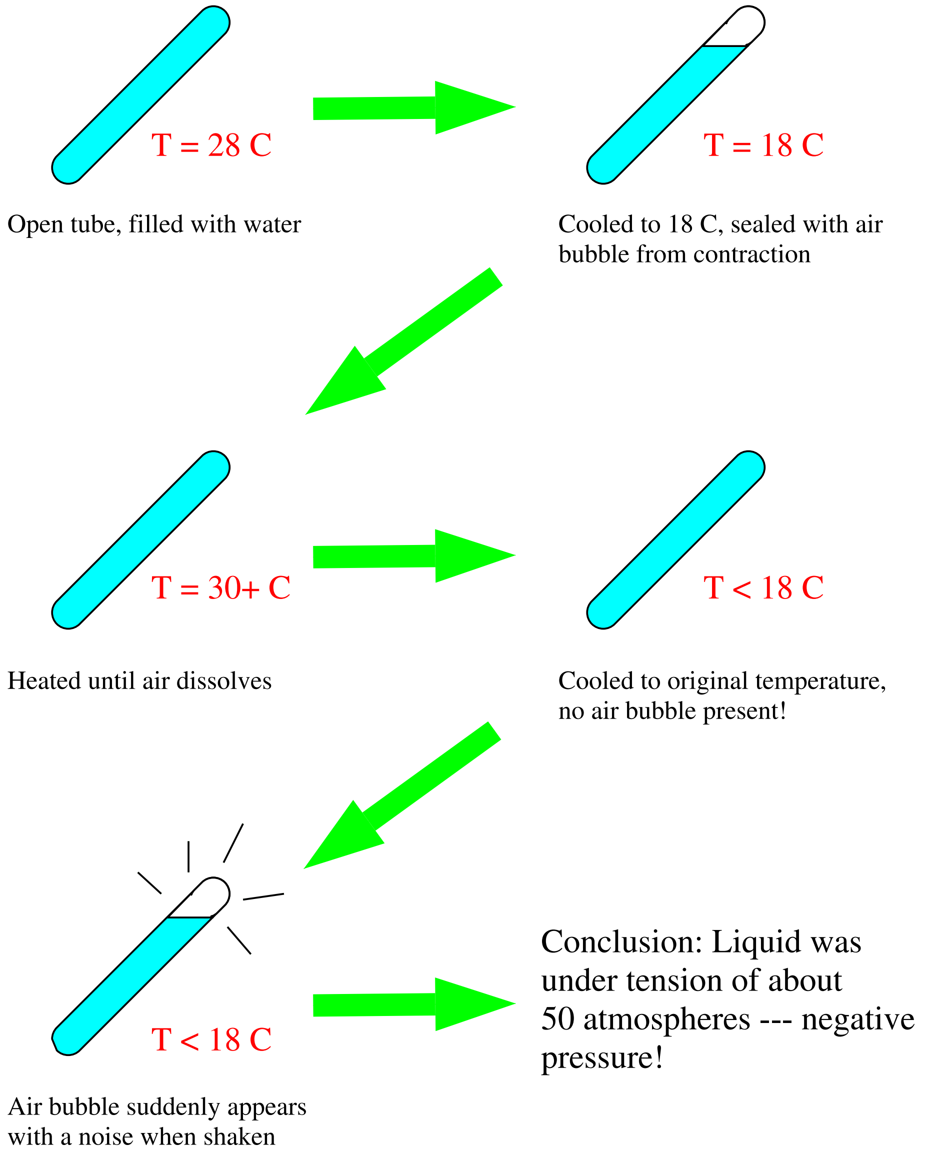
The interphase transfer terms $(\Gamma_{xy}, Q_{xy}, Q^{\Gamma}_{xy})$ are all functions of $\rho_m, X_n, T_m, T_l, T_s$, and T_w and are defined implicitly in the Radial Model.

Later Modifications

- Added additional fluids: potassium, sodium, mercury and silver
- Some problems matching experiments —
  Kinetic evaporation/condensation model to blame? No . . .
- Determined problem: liquid in tension (negative liquid pressure) was not being allowed by the code – see research by Berthelot

Berthelot's Experiment

France, 1850

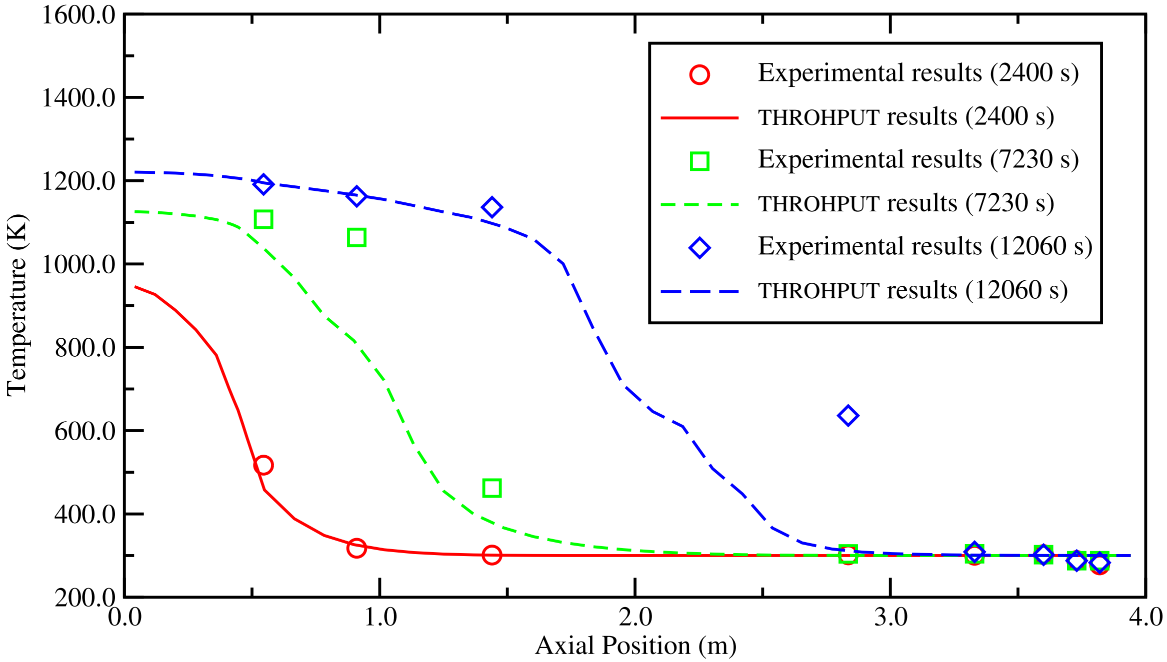


Conclusion: Liquid was under tension of about 50 atmospheres --- negative pressure!

Results: Problem Description

- LANL SPAR-8 heat pipe (3/8/85 test by Merrigan, Keddy and Sena)
- Lithium working fluid, Molybdenum pipe
- Lengths: 4.0 m total
  - 0.40 m evaporator
  - 0.09 m adiabatic
  - 3.51 m condenser
- Outside radius $\approx$ 1 cm
- Annular wick
- Initially frozen solid at 300 K
- Only heat output data available from experiment

Results: SPAR-8 Experimental Comparison



Only heat *output* data available from experiment, so

heat output used as heat input in the model.

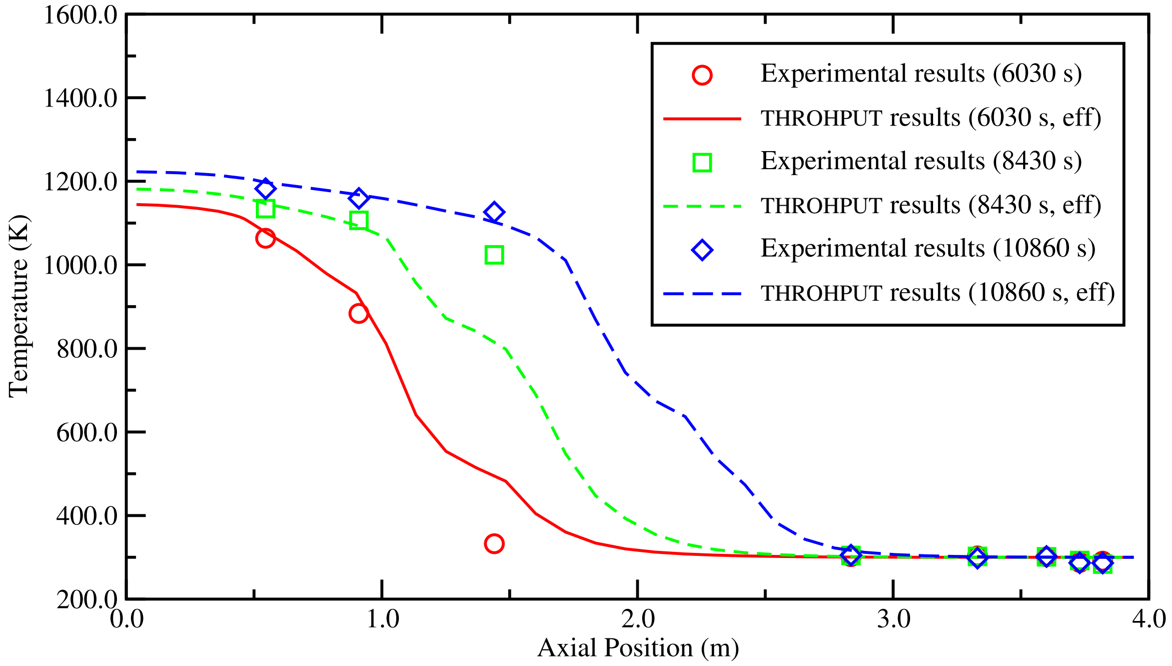
Why this assumption is realistic:

- Time history is similar
- Heat inputs are roughly the right scale

Why this assumption is not accurate:

- Time lag due to stored heat in the heat pipe
- Time lag becomes larger at later times – more heat storage

Results: SPAR-8 Experimental Comparison



To correct for time lag problems, use the same model run, but

set time-integrated heat output to the experimental value.

Why this assumption is realistic:

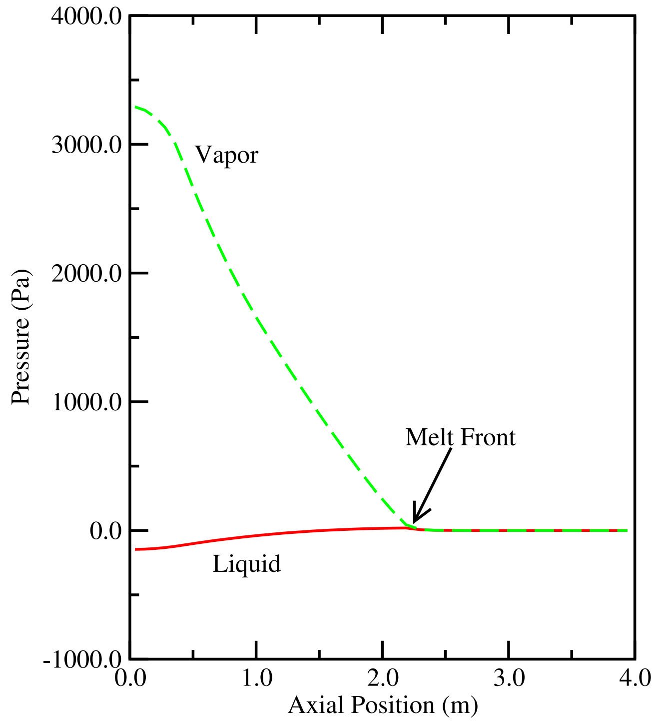
- Heat outputs are the same for both

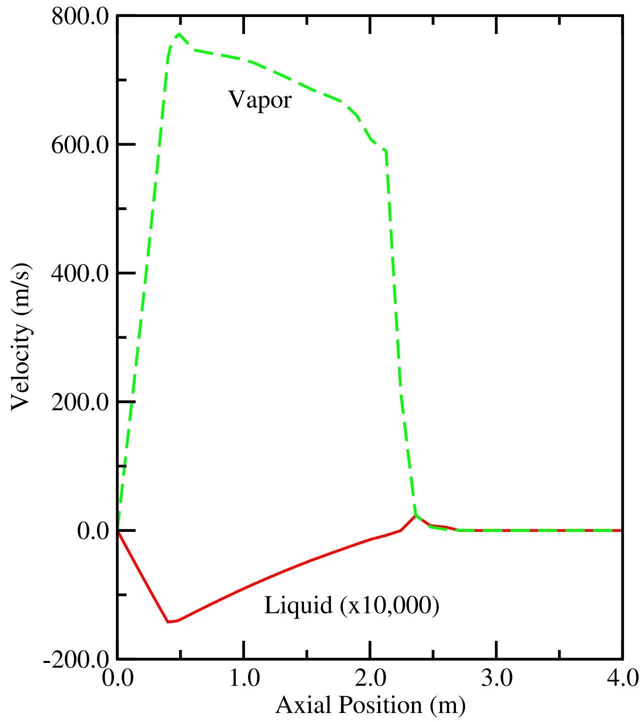
Why this assumption is not accurate:

- Timing is still incorrect

This gives better agreement later in the transient, but early time agreement degrades.

Results: SPAR-8 Pressure & Velocity Distributions at 13,260 s (3.68 hrs)





- Time is at end of transient
- Note negative pressure distribution – maximum liquid tension is -150 Pa
- Liquid velocity should be 53000 × vapor velocity for steady state – true for the model

CÆSAR Computational Physics Environment: Coding Characteristics

- Written in Fortran-95, preprocessed by Gnu m4.
- Object-based
- Parallel and serial versions, designed in from the beginning
- Completely levelized design – no dependency loops between classes or modules.
- Uses Design by Contract to verify the behavior of all procedures
- Uses extensive unit testing to certify all classes
- Uses the ideas of literate programming to generate documentation (in HTML, PostScript and PDF) from comments included in the code, via the Document Package (**`http://www.lanl.gov/Document`**).
- `http://www.lanl.gov/Caesar`

CÆSAR Computational Physics Environment: Numerical Modeling Characteristics

- Multiple mesh types (uniform, orthogonal, structured, unstructured, adaptive mesh refinement (AMR), triangular/tetrahedral, quadrilateral/hexahedral meshes)
- Multiple dimensions (1-D, 2-D and 3-D)
- Multiple geometries (cartesian, cylindrical and spherical)
- Multiple physics packages (diffusion, radiation transport, radiation hydrodynamics, fluid dynamics, magnetohydrodynamics and heat pipe thermal hydraulics)
- Multiple discretizations for partial differential equation terms
- Multiple external packages for linear solvers, communications, visualization, etc.

THROHPUT **Future Work**

- Production version of THROHPUT – Incorporation into CÆSAR
- Additional wick geometries (groove, arterial, slab)
- Arbitrary heat pipe cross-section (e.g. square)
- Two- or three-dimensional model
- Additional fluids and wall materials
- Entrainment model
- Graphical output
- User-specified heat pipe failure criteria
- Limit prediction (sonic, viscous, entrainment, capillary, boiling)